



Early Journal Content on JSTOR, Free to Anyone in the World

This article is one of nearly 500,000 scholarly works digitized and made freely available to everyone in the world by JSTOR.

Known as the Early Journal Content, this set of works include research articles, news, letters, and other writings published in more than 200 of the oldest leading academic journals. The works date from the mid-seventeenth to the early twentieth centuries.

We encourage people to read and share the Early Journal Content openly and to tell others that this resource exists. People may post this content online or redistribute in any way for non-commercial purposes.

Read more about Early Journal Content at <http://about.jstor.org/participate-jstor/individuals/early-journal-content>.

JSTOR is a digital library of academic journals, books, and primary source objects. JSTOR helps people discover, use, and build upon a wide range of content through a powerful research and teaching platform, and preserves this content for future generations. JSTOR is part of ITHAKA, a not-for-profit organization that also includes Ithaka S+R and Portico. For more information about JSTOR, please contact support@jstor.org.

THE
JOURNAL OF GEOLOGY

SEPTEMBER-OCTOBER, 1912

MICROSCOPICAL PETROGRAPHY FROM THE
QUANTITATIVE VIEWPOINT

FRED. EUGENE WRIGHT
Carnegie Institution of Washington

INTRODUCTION

The development of petrology has been along the lines of normal growth followed by other sciences. From the Stone age on, people have had to do with rocks and have gathered, in the course of the centuries, a vast amount of information about them, their characteristics, their modes of occurrence, and their uses in practical life. Different rock types have received different names, and, up to the last century, were classified according to their general appearance and the purposes they served. Fine-grained rocks, like phonolites, the component minerals of which could not be distinguished by the unaided eye, were considered homogeneous and grouped with minerals, until chemists were able to show by partial analysis that part of the rock was soluble in acid and part insoluble. With the advent of the petrographic microscope, a new and fascinating world was opened to the student of rocks, and for some decades the interest was centered in the qualitative description of rocks, their mineral composition, and their textures. It was virgin land for the petrologist to explore, and the methods he adopted were the methods of reconnaissance, analogous to those employed by the geologist, who

visits a new country, like Alaska, to obtain a general idea of the geologic lay of the land and the rock types there represented. During this reconnaissance period, petrography, or rock description, was the prominent feature of petrology, as the thick papers of that time testify. Men were interested in rock types and rock classification. They wished to cover the entire field, and to do so had, of necessity, to adopt the methods of reconnaissance. Their methods and their classifications were all essentially qualitative in nature. After this preliminary work came the more detailed investigations, such as are represented in geology by folio and economic work with large-scale base-maps and only limited areas to cover in a given time.

A science must always develop from the qualitative to the quantitative, and the process is necessarily a gradual one. In science the term qualitative is usually applied to statements in which no definite limits to the quantities involved are expressed, while in quantitative statements such limits are definitely set. These limits may vary widely in their order of magnitude and one quantitative statement may be only roughly quantitative (first approximation) while a second may be highly precise. No observations are ever absolutely accurate; the absolute quantitative cannot be attained in the physical world and the idea of limits or degrees of approximation to truth (probable error) pervades all science. Such limits establish at once boundary lines or fences within which speculation must be held. In a qualitative statement such limits are not given, with the result that they may be arbitrarily extended or decreased by the investigator as the exigencies of his case demand. The smaller the limits in quantitative statement the higher the degree of approximation to truth, the fewer the possibilities for misinterpretation, and the greater the probabilities for correct generalization by the scientist. The growth of a science rests, in part at least, on the development of exact methods of attack and on the precise data of measurement accumulated thereby.

The observer who applies only reconnaissance methods to detailed work requiring exact methods is doing an injustice to the work, and is actually wasting his time, because such work has to

be done over later on. A mechanic who attempts to make a fine spirit level or microscope with poor tools cannot produce a good job. A petrologist on detailed work who describes rocks in the way they were described thirty years ago, and uses the microscope as it was then used, is doing an injustice, not only to the reader, but to the microscope and the tools of precision which are now placed at his disposal.

There is a genuine pleasure on the other hand, in making the most out of the tools we have, and in gathering data, the accuracy of which we know definitely and can state in terms which will be intelligible to observers a century hence. In short, it is only by the accumulation of tangible facts, and grouping of such facts by correct generalization, that real progress is made. From a few facts a mind of genius may intuitively infer and state a correct generalization which covers a whole group of facts to be discovered later, but most of us are not in that class, and it is our duty to assemble the facts—facts which are real facts, based on precise data of observation.

Strictly speaking, quantitative work means control over all parts of a given system. The order of accuracy of all measurements made is definitely known and any observer at a later date should be able to repeat the measurements and obtain similar results. The system is, in short, reproducible. Quantitative work is tangible throughout and we know definitely its behavior at all times during our observations. In qualitative work, on the other hand, the system is imperfectly defined, no definite limits are set, and the results, obtained, lack precision; their probable error is unknown and they are indefinite and uncertain to that extent. A strictly quantitative piece of work, the accuracy of which is adequately stated, produces on the observer, and on the reader as well, a feeling of confidence and stability, which qualitative work with its uncertain elements can never produce. A sense of control and mastery over the factors of an intricate system is a natural sequence of good quantitative work and is, psychologically, one of the greatest rewards granted to the student of nature.

There is still another feature which may be emphasized. In

attacking a problem, the different methods employed should be of about the same order of accuracy. It is useless to conclude that because precise methods are used on one part of a problem, the final result will be of the same order of accuracy, no matter what other methods are employed. The different methods should be co-ordinated and the observer should exercise proper judgment in applying his methods. Thus in rough traversing it would be a waste of time to use a theodolite and to read angles to seconds and then to measure the distances by pacing; or, vice versa, to attempt accurate triangulation with a pocket compass even though the base line be most carefully measured. There are cases, on the other hand, where certain mechanical operations, which are complete in themselves, can be readily and accurately performed, as, for example, the weighing of chemical precipitates; in this instance, it would be obviously improper to weigh the precipitate on a rough hand-balance, even though the probable error, resulting from such a procedure, might be within the probable error of the chemical methods employed. The order of accuracy of the final result would be unnecessarily decreased thereby, since its probable error is a direct function of the probable errors of the different steps involved in the process. To apply these principles successfully to actual problems requires critical judgment on the part of the observer.

All of this seems obvious, but it is not always realized in practice. Instruments are used, but their adjustment is rarely tested. Extinction angles are measured to the minute, and so stated, but the observer may fail to test the adjustment of his microscope and the nicols may be out half a degree or more.

The same holds true of the use of quantitative data. From a series of known facts a scientist evolves a theory and then searches for further data to substantiate or disprove his theory. This course of procedure is right, provided he examine critically into the data themselves—how they were obtained, their probable errors, and so forth.

The use of mathematics in this connection is important. Mathematics is a system of highly perfected logic, expressed in the form of symbols, and can be applied to practically all problems

in which the quantitative element enters. It is a highly developed system and impressive to most of us but "Huxley warned us that the perfection of our mathematical mill is no guaranty of the quality of the grist."¹ If we put into our mill loose data with large probable errors we cannot expect our final results to be more than first approximations. The more accurate, the initial data the more accurate and satisfactory the final result. A statement cast in mathematical form does not prove that it is correct even though the mathematics be rigidly true. Mathematics, because it is logical and concise, is often used to express, in general form, relations the exact numerical values of which are not definitely known—such values being then represented by appropriate symbols. For purposes of generalization and the framing of a theory by the logical grouping of observed facts into a simple co-ordinated system, mathematics is invaluable because it serves to express in a single sentence the results and essentials of a whole course of reasoning. The more accurate the facts and results thus used, the greater the degree of probability for correct generalization and the easier the process of such generalization. The non-mathematical reader may examine the premises on which any mathematical argument is based and then use his common-sense in testing the conclusions.

Quantitative work requires more time than qualitative work but petrography has now reached a stage where quantitative work is required. To the observer accustomed only to rapid qualitative methods, quantitative methods necessarily seem slow and irksome and not yielding of immediate results, and he may even be tempted to question whether such methods are really worth the while and repay the energy and time which must be put into them. But in petrography the qualitative reconnaissance period has passed and it is no longer permissible in good work to ignore the quantitative element altogether. It is only by the accumulation of precise data that many of the large problems of petrology will be solved, and until then the solutions will remain matters of opinion supported more or less by a slender foundation of fact. Never before has the need for exact evidence, both from the field and

¹ Extract from address by R. S. Woodward, "On the Mathematical Theories of the Earth," *Proc. Amer. Ass. Adv. Sci.*, 1889, p. 62.

from the laboratory, been felt in petrology as it is today. The pioneers have done the reconnaissance work for us and we must proceed along quantitative lines of attack before we can hope to obtain even approximate solutions of the big problems ahead. Each one of us may contribute his share and add his little stone to the structure by adopting the quantitative viewpoint and realizing its importance in his attitude toward science in general and petrology in particular. In petrology *the quality of our quantitative work is far more important than the quantity of our qualitative work.*

Having now considered the standards postulated by modern petrology, our next step will be to show that the present-day tools and methods of microscopical petrography measure up to these requirements and are furthermore easy of application and simple in principle. We base our judgment of the value of a tool or method on its effectiveness, its simplicity, its adjustable sensibility, and its range of applicability. An instrument whose sensibility can be adjusted to meet the different conditions of observation which may arise is obviously superior to an instrument whose sensibility is rigidly fixed and adapted for only one particular set of conditions. The range of applicability as a feature in any instrument should not be carried too far because practical experience has shown clearly that the so-called universal instruments are, as a rule, unsatisfactory and often do not accomplish in a thoroughly competent manner any one of the several purposes for which they are intended. To fulfil a given set of conditions adequately, it is usually necessary that a special instrument be designed for the purpose. Thus, a small caliber rifle may be admirably suited for small game, but for larger game it is wholly inadequate, and may do more harm than service in an emergency; vice versa, a large caliber rifle is of little value for hunting small game.

The first tools which are devised for a given purpose are usually affected by "children's diseases," as Dr. A. L. Day has expressed it, and only by careful mechanical attention can such troubles be eliminated. The instruments and methods of microscopical petrography have in large measure passed through and beyond this stage and have been developed to such an extent that practically all the optical properties of mineral grains can now be

determined easily and without complicated apparatus on favorable plates or grains 0.02 mm. in diameter and over. It may be of interest to indicate briefly a few of the methods which experience has shown to be most satisfactory in actual work.

ADJUSTMENT OF THE PETROGRAPHIC MICROSCOPE

In these methods it is assumed that the microscope is properly adjusted, otherwise the results obtained may be seriously in error. The simplest method for testing the adjustment of the petrographic microscope is probably the following: (1) Remove from the microscope all lenses—ocular, objective, and condenser—and point it directly at the sun whose rays are parallel and so intense that a rotation of less than 1° of one of the nicols from the position of total extinction is readily discernible. When the nicols are accurately crossed the sun appears as a dim disk in the dark background. (2) Test the adjustment of the cross-hairs of the ocular to the principal planes of the crossed nicols by observing under the microscope (fitted with ocular and centered objective but not with condenser, and pointed directly at the sun) a cleavage plate of some mineral, as anhydrite, celestite, or anthophyllite, which shows parallel extinction. The cross-hairs of the ocular should then be parallel with the cleavage edge of the plate in its position of total extinction. (3) Insert the condenser and note that it is properly centered when the image of the substage diaphragm occupies the center of the eye-circle of the ocular. In this plan of adjustment the assumption is properly made that the draw tube and the substage are in alignment and that the optical elements are correctly mounted—mechanical details which are satisfactorily met by modern instrument-makers.

THE OPTICAL PROPERTIES OF MINERALS

Passing now to the optical and crystallographical features on which mineral diagnosis under the microscope is based, we shall consider first their nomenclature. Both theory and experience have shown that for monochromatic light the variation in the optical properties of a given mineral with the direction can be adequately expressed and defined in the most general case by

reference to a triaxial ellipsoid, the principal axes of which are equal to the three principal refractive indices. Having given the lengths and positions of the three principal axes of this *optic ellipsoid* within the crystal, it is possible to predict definitely the optical behavior of any section cut from the crystal. The validity of the optic ellipsoid has been proved so frequently and its usefulness in practical work is so great that its importance, independent of all theory, in optical work cannot be too strongly emphasized. That this has not been adequately done in the past, is evident from the current terms used to designate the optical properties of a mineral and of a mineral section. Thus we determine whether a mineral is isotropic, uniaxial, or biaxial and classify it accordingly, but there is no collective term which states that by this determination we actually ascertain the particular type of optic ellipsoid by which the optical behavior can be expressed; whether by a triaxial ellipsoid in which the three principal axes are unequal, or by an ellipsoid of revolution in which one axis is unique and different in length from the other two equal axes, or by a sphere in which all three axes are of the same length. For this characteristic the term *optic ellipsoidity*¹ is here suggested as a suitable group expression; thus the *optic ellipsoidity* of a *biaxial* mineral may be considered *biaxial* (two axial ratios being required to define the shape of its ellipsoid); the *optic ellipsoidity* of a *uniaxial* mineral, *uniaxial* (one axial ratio being sufficient to define the shape of its optic ellipsoid); and the *optic ellipsoidity* of an *isotropic* mineral, *isoaxial* (the three axes of its optic ellipsoid being equal). The *optic ellipsoidity* of a mineral is one of its most important diagnostic features; it is employed as a primary group-characteristic in nearly all the determinative tables for use with the petrographic microscope which have been published.

The lengths of the principal axes of the optic ellipsoid are ascertained by measuring the *principal refractive indices* of the crystal. From these in turn the *principal birefringences*, the *optic axial angle*, and the *optical character of the mineral* can be derived; these last properties are, therefore, subordinate, in a

¹ The writer is indebted to Mr. C. E. van Orstrand of the U.S. Geological Survey for aid in devising both this term and the expression *optic ellipsity* noted below.

measure, to the refractive indices. But in ordinary mounted, thin sections no satisfactory method has yet been devised for measuring the refractive indices directly and the microscopist is forced, in consequence, to make use of the other properties which can be ascertained under these conditions but which do not express, even in aggregate, all the information embodied in the simple statement of the refractive indices. It is for this reason especially that so much emphasis is placed on methods for refractive index determination and in particular on the immersion method by means of which the refractive indices of minute, isolated mineral grains 0.01 mm. and over in diameter can be readily measured with a fair degree of accuracy.

For the complete description of the optical behavior of a mineral, it is essential to determine not only the lengths of the principal axes of the optic ellipsoid but also its position within the crystal. This is usually accomplished by means of *extinction angles* on crystal faces of known orientation. From the position of the optic ellipsoid within the crystal we are able to infer the system in which the mineral crystallizes, since this position depends, as Brewster was the first to show, on the symmetry of the crystal itself. By determining the *principal refractive indices* of a mineral and its *extinction angles* on plates of known orientation, we can thus define its *optic ellipsoid* and its *crystal system* and from these in turn derive the optical behavior of any section cut from the crystal.

Having given the optic ellipsoid of a mineral for a particular color of light, the directions of vibration (positions of extinction between crossed nicols) and the relative velocities of light waves entering normally to any given section of the mineral can be ascertained by considering the section to pass through the center of the optic ellipsoid and to cut out of the same an ellipse, along the major and minor axes of which the light vibrations take place and produce plane-polarized light waves, whose velocities of transmission are inversely proportional to the lengths of these axes. This ellipse may be called the *optic ellipse* of the section. The optic ellipse is completely defined when the length of its major and minor axes (refractive indices γ' and α') and their positions with

respect to some definite crystal direction in the plate (extinction angle) are given. In actual determinative work with thin sections, the lack of a satisfactory method for measuring refractive indices directly under the microscope is a serious difficulty and the observer is compelled to make use of other properties, as *birefringence* and the *relative axial lengths* or *axiality* of the *optic ellipse*, which can be determined under these conditions but which, as noted above, are less important than the refractive indices and do not express, even together, as much as the refractive indices do alone.

For the expression *axiality of the optic ellipse* the collective term *optic ellipsity* may be used to express the relative lengths of the axes of the optic ellipse of the section. This term is preferable to the usual term *optical character of the section* or *optical character of its elongation*. The term *optical character* serves primarily as a group expression for the terms *optically positive* and *optically negative*. Its further use, in the above sense as a term implying the determination, in plane-polarized light, of the relative lengths of the axes of the optic ellipse of any given section is not justifiable, because, in that case, the same term serves two masters and conveys to the mind two totally different impressions; and such usage is not conducive to precise statement. The term *optic ellipsity* or *axiality of the optic ellipse* may well be substituted for *optical character* in its second usage.

In practical mineral determination under the microscope the observer may ascertain, in monochromatic light: (a) the *optic ellipsoidity* of a mineral, whether *biaxial*, *uniaxial*, or *isoaxial*; (b) the absolute lengths of the principal axes of its optic ellipsoid ($=\alpha, \beta, \gamma$, the *principal refractive indices*); (c) the difference in absolute lengths of any two of the principal axes of its optic ellipsoid ($=$ *principal birefringences*); (d) the angle between the normals to the two circular sections of the optic ellipsoid ($=$ *optic axial angle*); (e) the principal axis which bisects the acute angle between the normals to the two circular sections of the optic ellipsoid (the *acute bisectrix* γ or α and with it the *optical character of the mineral* whether *positive* or *negative*); (f) the relative position of the optic ellipsoid within the crystal (usually ascertained by

means of *extinction angles* on known crystal faces) and with it the *crystal system* of the mineral.

Similarly for any given crystal section we can determine, in parallel polarized light, (a) its *optic ellipsity* or the *axiality of its optic ellipse* (relative lengths of the two axes of its optic ellipse); (b) its *refractive indices* γ' and a' (lengths of the major and minor axes of its optic ellipse); (c) its *birefringence* (measured by the difference in lengths of the major and minor axes of its optic ellipse); (d) relative positions of the axes of its optic ellipse to any crystallographic direction observed on the section (*extinction angle*).

These properties vary to a certain extent with the color of light used and give rise to phenomena of color and color dispersion which are useful in mineral diagnosis. These are briefly: *color*; *pleochroism*; *absorption*; *dispersion of mineral*; *variation in the principal birefringences*; *dispersion of the bisectrices*; *dispersion of the optic axes*.

With this brief statement in mind of the optical features which are made use of in practical mineral determination, it will now be in order for us to show that the methods of microscopical petrography measure up to the requirements emphasized in the introduction and are furthermore simple and easy of application. For this purpose it will be convenient to group the optical and crystallographic properties into two classes: those of the first class (*optic ellipsoidity, optic ellipsity, optical character of mineral, color, pleochroism, absorption, dispersion of the optic axes, dispersion of the bisectrices, crystal habit*) being ascertained ordinarily by direct observation without measurement, while for the second class (*refractive indices, birefringence, extinction angles, optic axial angles, cleavage angles*) the numerical results of actual measurement are required. This distinction is drawn somewhat arbitrarily and is not meant to imply that the properties of the first group are strictly qualitative in their nature but that they are treated at the present time in ordinary petrographic microscopic work as qualities of an object rather than quantities which must be definitely measured. With greater refinement in the methods of determination, some of the properties of the first class will un-

doubtedly be included in the second essentially quantitative group. In the following paragraphs a concise description of the essentials of a few of the best available methods for the determination of these properties will be given.

DETERMINATION OF THE OPTICAL PROPERTIES OF THE FIRST CLASS

For this group few new methods of determination have been developed in recent years; *color, pleochroism, absorption, crystal habit, dispersion of the optic axes and of the bisectrices* being ascertained by practically the same methods which have been in use since the introduction of the petrographic microscope.

The optic ellipsoidity.—In the determination of this feature, two methods, in particular, have proved useful in recent years: (a) Uniaxial minerals are readily distinguished from biaxial minerals, by noting that the achromatic brushes (zero isogyres) in interference figures from uniaxial plates are parallel with the principal nicol planes and pass through the center of the field on rotating the stage, while in biaxial minerals the dark bars (zero isogyres) of the interference figure rotate on rotation of the stage and may include any angle with the principal plane of the polarizer. If the dark axial bar in an interference figure does not remain straight and in the same azimuth on rotating the stage, the optic ellipsoidity is biaxial; otherwise the birefracting mineral is in general uniaxial.¹ (b) To ascertain whether a very weakly birefracting plate is isotropic or birefracting and at the same time to determine the relative value of the axes of its optic ellipse (its optic ellipsity), the sensitive tint plate should be inserted, not in the diagonal position as is usually the case, but in such a position that the axes of its optic ellipse include only a small angle with one of the principal nicol planes; under these conditions the field illumination due to the sensitive tint plate itself is very slight while its path difference is still effective. The changes in the faint color hues from the mineral grain are clearly visible against the darker background and extremely minute traces of birefringence can thus

¹ See F. Becke, *Denkschr. Wiener Akad. Wissen. Math.-Natur. Kl.*, LXXV, 1904; *Tscherm. Min. Pet. Mitteil.*, XXIV, 30, 1905; XXVII, 177-78, 1908.

be detected.¹ If the sensitive-tint plate be inserted in the diagonal position, it illuminates the field so strongly that the faint color differences from the mineral grain are veiled and often completely lost to view, especially if the grain be minute. The same method is applied with equal success to the determination of the optical character of very weakly birefracting minerals in convergent-polarized light.

The optical character can be determined on all sections in which at least one optic axis appears in the field by noting that the convexity of the axial bar (zero isogyre) passing through the optic axis is always directed toward the acute bisectrix.² On sections, perpendicular to the optic normal the acute bisectrix can be located by noting that the faint achromatic hyperbolas of the interference figure pass out of the field in the direction of the acute bisectrix³ on rotating the stage. In case the plate is so thick that the interference colors are bright, the position of the acute bisectrix can also be ascertained by noting that the interference color is relatively lower in the quadrants containing the acute bisectrix than in the adjacent quadrants.⁴ In thin rock sections the mineral plates of weak to medium birefringence do not often exhibit interference colors much above pale yellow of the first order and for such plates the second method is inadequate and the first should be used. The relative value of the acute bisectrix whether

¹ See F. E. Wright, "The Methods of Petro. Microsc. Research," Carnegie Inst. Washington, *Pub.* 158, 73, 1911. In the writer's microscope the sensitive tint plate is mounted in a rotating collar beneath the substage condenser and can be turned quickly from one quadrant to another, thus greatly facilitating its use in rapid routine work.

² The following concise statement of the rule for finding the sign of reaction of a section has recently been given by F. Rinne (*T.M.P.M.*, XXX, 321-23, 1911): A central uniaxial interference figure divides the field into four quadrants. Let the NE and SW quadrants be considered positive as usual and the adjacent quadrants negative. In biaxial minerals the areas NE and SW of the achromatic brushes (zero isogyres) taken with respect to the acute bisectrix may in like manner be considered positive. If now the sensitive tint plate be inserted so that the major axis γ of its optic ellipse points NE, SW, then the mineral is *optically positive* when the *positive quadrants or areas* of the interference figure are colored *blue* and *negative* when the *negative areas* are colored *blue*.

³ F. E. Wright, *Amer. Jour. Sci.* (4), XVII, 387, 1904.

⁴ F. Becke, *T.M.P.M.*, XVI, 181, 1897.

α or γ (the *optic ellipticity* of the section) can then be ascertained by use of the sensitive tint plate or by the quartz wedge in parallel polarized light.

MEASUREMENT OF THE OPTICAL PROPERTIES OF THE SECOND CLASS

A number of new methods have been suggested in recent years for the measurement of the optical properties of this class, with the result that satisfactory methods are now available for use even on minute mineral grains; the accuracy of the results attainable by these methods under the different conditions is known and the application of these methods is now a matter of routine.

Refractive indices.—For the measurement of refractive indices of minerals in the mounted thin section no accurate method has yet been devised; but on unmounted mineral grains and plates, measuring 0.01 mm. and over in diameter, the refractive indices can be readily determined by the immersion method with an accuracy of ± 0.001 for sodium light on isolated favorable sections. For this method a set of liquids of known refractivity is essential. The following set is used at present in the Geophysical Laboratory:

Refractive Indices	Mixtures of
1.450–1.475	Kerosene and turpentine
1.480–1.535	Turpentine and ethylene bromide or clove oil
1.540–1.635	Clove oil and α -monobromnaphthalene
1.640–1.655	α -monobromnaphthalene and α -monochloronaphthalene
1.660–1.740	α -monobromnaphthalene and methylene iodide
1.740–1.785	Sulfur dissolved in methylene iodide
1.790–2.050	Methylene iodide, arsenic sulfide, sulfur and tin iodide. ¹
2.055–2.750	Glass produced by melting amorphous sulfur and selenium in different proportions. The mineral grains to be tested are immersed in the molten liquid but are examined after it has cooled and hardened to a red-colored glass. ²

¹ Dr. H. E. Merwin of this laboratory has recently made a detailed study of these highly refracting mixtures, their preparation, and their permanency. The results of his work are to appear shortly in the *Amer. Jour. Sci.*

See also O. Maschke, *Pogg. Ann.* CXLV, 565, 1872; *Wiedemann's Ann.*, XI, 722, 1880; J. Thoulet, *Bull. Soc. Min. France*, III, 62, 1880; H. Ambronn, *Ber. Sächs. Gesell. d. Wissen. Math. Phys. Kl.*, 1–8, 1896; J. L. C. Schroeder van der Kolk, *Zeitschr. f. Wissen. Mikrosk.* VIII., 458, 1898; F. E. Wright, *T.M.P.M.*, XX, 239, 1901; *Amer. Jour. Sci.* (4), XVII, 385, 1904; Carnegie Inst. Wash. *Pub.* 158, p. 98, 1911.

² The refractive indices of these glasses were measured in lithium-light and not in sodium-light, as is the case with all the liquid mixtures in this list.

In this series the refractive index of each liquid for sodium light is 0.005 higher than that of the liquid immediately preceding it. In choosing these liquids the guiding factors were stability, miscibility, and low dispersion. The refractive indices were measured on a total refractometer up to 1.74; above this by the hollow-prism method in sodium light. In place of the hollow prism Dr. Merwin has recently found a prism satisfactory which is made by fusing two narrow strips of plane glass (selected microscope object glass) together at one end so that their plane surfaces below the joint include an angle of 35° to 45° . A drop of the highly refractive liquid is then placed in the wedge-shaped space between the glass plates and adheres by capillarity to their plane surfaces, thus assuming the required prism shape. The liquids are kept conveniently in small dropping bottles with ground-glass stopper and cap, which interposes two ground joints to prevent evaporation. Experience has shown that the liquids so kept do not vary over 0.002 in a year, while the average change in the refractive index of a liquid is about 0.001 decrease for every 3° C. rise in temperature. By using obliquely incident light or by observing the Becke line, it is possible to ascertain at a glance whether the refractive index of a particular grain is above, below, or about equal to, that of the liquid.

In case the mineral grain has a higher refractive index than the liquid, it acts as a lens on an incident pencil of rays and increases their convergency; if its refractivity is lower than that of the liquid, it diverges the incident rays. This difference in behavior is best shown by a pencil of oblique rays; these are concentrated on the distant side of a higher refracting mineral grain opposite to that at which the incident rays impinge; in a lower refracting grain they are concentrated on the near side. In both instances the two margins of the mineral grains appear unequally illuminated; if the light be incident from the left, the bright band of light appears on the right margin of the higher refracting grain, and on the left margin of the lower refracting grain. In case both mineral and liquid have the same refractivity for yellow or green light, the difference in dispersion between liquid and mineral gives rise to characteristic phenomena. The dispersion for liquids is in general

greater than that for solids and in the present instance the liquid will have a lower refractive index than the mineral for red and a higher refractive index for blue, with the result that the red rays are concentrated along the one margin of the grain and the blue rays on the opposite side. The grain appears fringed with colored margins, red or orange on the one side and pale blue on the opposite side. If the intensity of illumination on both sides of the grains is about equal, the refractive index of mineral and liquid are equal for the central part of the visible spectrum.

Obliquely incident light is most readily obtained by placing the forefinger between the substage reflector and the polarizer and casting a shadow over half the field. The error of such a determination in white light is less than ± 0.005 on good sections, while if monochromatic light be used and care taken to select clear single grains, the error may be reduced to ± 0.001 . If the grain be anisotropic, the three principal refractive indices α , β , γ can be determined by placing the grain in such positions that the parallel polarized light waves from the lower nicol vibrate, in passing through the crystal, parallel to one of the three principal axes of the optic ellipsoid.

The chief difficulty in the measurement of the refractive indices of minute grains or plates in the thin section, is one of mechanical subdivision; the grains occur frequently in fine, overlapping aggregates, often imbedded in glass; and it is not an easy task under these conditions to find a clear, isolated grain on which measurements can be made.

The materials for the set of refractive liquids noted above can be readily obtained from dealers in chemical supplies and the entire series prepared for use in a few hours' time. With the set of refractive liquids at hand the refractive indices of a mineral grain can be readily ascertained within ± 0.005 and one of the most important optical constants of the mineral thus determined. It is a matter of surprise, in view of the ease and facility with which this method can be applied, that it is so little used by petrologists and by chemists.

Birefringence.—For the measurement of birefringence, extinction angles, and optic axial angles a specially constructed ocular

has been found convenient.¹ This ocular consists essentially of a metal holder, which fits into the microscope tube as an ordinary ocular and acts as a support for certain plates which are inserted in the lower focal plane of a Ramsden eyepiece above. Cross-hairs are attached to the base of the cylinder support for the Ramsden eyepiece and are viewed by it simultaneously with the upper surfaces of the inserted wedges or plates.

For the measurement of the birefringence a graduated combination quartz wedge is used which is so cut that the 0.1 mm. divisions of the scale on its upper surface give directly path differences in $10\ \mu\mu$ for sodium light. By its use together with a cap nicol, the path difference in sodium light or order of interference color in white light can be readily ascertained, the wedge being inserted in the diagonal position until the black band of exact compensation is reached; the division of the scale covered by the black band is then the path difference in $10\ \mu\mu$. In the case of thick plates the point of the line of compensation should be first determined approximately in white light; otherwise the correct line of compensation may not be selected when monochromatic light is used. The path difference is directly dependent on two factors: the thickness of the plate and its birefringence. The simplest method for obtaining the thickness of a mounted plate or grain is to focus with a high-power objective first on its upper surface and then on its lower surface, as seen through the plate or grain itself. The amount of movement of the fine adjustment screw during this operation is the apparent thickness of the plate or grain, provided, of course, the fine adjustment screw is accurately constructed. The true thickness is obtained by multiplying the apparent thickness by the average refractive index of the plate. Experience has shown that under these conditions an error of 5 or even 10 per cent² may be made, especially if the plate be very thin, on thicker plates and grains the percentage error, due to imperfect focusing, is correspondingly less. To insure greater accuracy, the average of a series of determinations on the same plate should therefore be taken.

¹ F. E. Wright, *Amer. Jour. Sci.* (4) XXIX, 415-26, 1910.

² See F. E. Wright, *Amer. Jour. Sci.* (4), XXIX, 416, 1910.

The quotient of the two values thus obtained—path difference divided by thickness of plate—is the birefringence. The probable error of the determination under these conditions with good sections may be 10 per cent; for ordinary minerals this means an error of one or more units in the third decimal place.

The extinction angle for a given crystal face is the angle between a definite crystallographic direction on the face and one of the axes of its optic ellipse. With sharply developed crystallites or with minerals exhibiting sharp cleavage lines the error resulting from incorrect setting of the crystallographic direction parallel with the vertical cross-hair in the ocular is practically negligible; with less sharply defined crystallographic directions, the settings are of course less accurate; but as this is due to the crystal development and not to the method, the observer can only accept the situation as he finds it; the only probable error over which he has direct control centers essentially in the determination of the position of extinction. Since the eye is sensitive only down to a certain limit (threshold value, on an average about 0.001 meter-candle), it is evident that for all positions of the crystal plate between crossed nicols for which the intensity of the emergent light is below this limit, the plate will appear dark. In ordinary microscope work the angular range of this area of darkness varies from 1° to 2° , depending on the conditions of illumination and the eye of the observer; the error of a single determination may amount to 1° under certain conditions. By repeating such determinations the probable error can be materially reduced. But more accurate results can be obtained by using special devices which have been constructed for the purpose. Of these the bi-quartz wedge plate¹ has the advantage of adjustable sensibility to meet the different conditions of observation which arise. It is a combination of a right-handed quartz plate with a left-handed quartz wedge, and of a left-handed quartz plate with a right-handed wedge, all cut normal to the axis and so mounted that the points of exact compensation in each half are in alignment. The position of extinction of a mineral is determined with this device by noting that, on its insertion, the parts of the mineral plate covered by the adjacent

¹ F. E. Wright, *Amer. Jour. Sci.* (4), XXVI, 377-78, 1908.

halves of the wedge show the same degree of illumination. If the mineral be not in the position of total extinction the halves are not equally illuminated. Experience has shown that with this device the probable error of a single setting on a favorable section is about $\pm 10'$. The bi-quartz wedge plate is mounted in a metal carriage which in turn fits into the ocular holder described above. This bi-quartz wedge plate may also serve on dark days for the adjustment of the nicols in the petrographic microscope.

Optical axial angles are most readily measured by means of the 0.1 mm. co-ordinate micrometer disk¹ which in its metal-mounting fits in the ocular holder noted above. On favorable sections (0.025 mm. and over in diameter) the probable error of measurements with this plate is about $\pm 1^\circ$ in case both optic axes appear in the field of vision and $\pm 3^\circ$ in case only one optic axis is visible. For measurements on mineral grains, the particles should be immersed in a liquid of the refractive index β to eliminate errors due to refraction on the uneven surfaces of the grains. In weakly birefracting substances and interrupted sections the axial bars are less sharply defined and the values obtained thereon are correspondingly less accurate.

The divisions of the co-ordinate micrometer disk serve to locate the position of any point in the field. The interference figure, observed, is practically an orthographic projection of the interference figure formed in the upper focal plane of the objective and the use of co-ordinates to locate points in the field is therefore permissible. The angular values represented by these co-ordinates are determined, once for all, by means of an Abbe apertometer, or a graduated sphere or a scale in the lower focal plane of the sub-stage condenser.² In case both optic axes, A_1 and A_2 , appear in the field the course of procedure is simple. The crystal plate is turned until the plane of the optic axes, A_1A_2 , in the interference figure (observed, together with the co-ordinate micrometer scale after insertion of the Bertrand lens, in the lower focal plane of the

¹ F. E. Wright, *Amer. Jour. Sci.* (4), XXIV, 316-69; XXIX, 423, 1910; XXXI, 157-211, 1911.

² These are discussed at length in *Amer. Jour. Sci.* (4), XXIV, 317-69, 1907; also in *Carnegie Inst. Washington, Pub.* 158, 1911.

Ramsden ocular) is parallel with the horizontal cross-hair of the ocular and its distance in this position from the center of the field recorded. The crossed nicols are then turned through a suitable angle (30° or 45°). The axial bars rotate in the opposite direction but the optic axial points, A_1 and A_2 , remain stationary and dark; they are situated at the intersection of the axial bars with the horizontal line which marked the plane of the optic axes. The angular distance between the two optic axial points A_1 , A_2 , thus determined, is directly the optic axial angle $2E$ in air.

In case only one optic axis A_1 appears in the field of vision the method is more complicated and less accurate but in view of its usefulness it may be briefly outlined. It is based primarily on the rule of Biot-Fresnel which states that for light waves propagated in any given direction in a crystal the two lines of vibration bisect the angles between the projections of the two optic axes on the plane normal to the given direction of propagation. In an interference figure the line of vibration for any point which appears dark between crossed nicols is evidently contained in the extinguishing plane of the analyzer—otherwise it would not be dark. The plane of vibration for all points on the achromatic brushes (zero-isogyres) of an interference figure is therefore known. By locating the optic axis A_1 and any point P on the achromatic brush it is accordingly possible by applying the Biot-Fresnel rule to determine graphically the position of the second optic axis.¹ After having made the measurements in the interference figure, the observed co-ordinate values are first reduced to equivalent angular values in air and these in turn to corresponding values within the crystal by means of its average refractive index. These angles are then plotted in suitable projection (angle or stereographic)—the plane of the optic axes as a great circle parallel with the horizontal diameter, the principal plane of the polarizer in its two azimuths as diameters of the projection, the optic axis A_1 and the point P on the achromatic brush at the intersection of the recorded small circle (almucantar) co-ordinates. In this pro-

¹ See F. Becke, *T.M.P.M.*, XXIV, 35-44, 1905; XXVIII, 290, 1909; also F. E. Wright, *Amer. Jour. Sci.* (4), XXIV, 316-69, 1907; (4), XXXI, 157-210, 1911; Carnegie Inst. Wash. *Pub.* 158, 147-200, 1911.

jection the Biot-Fresnel rule is applied by first projecting the optic axis A_1 on the polar circle of the point P ; the intersection, C , of this polar circle with the diameter which defines the position of the principal plane of the polarizer at the time of the observation determines in projection the line of vibration of P . The angle between the point C and the projection point A'_1 of the optic axis A_1 is half the angle between the lines of projection of the two optic axes. The point A'_2 , the projection of the second optic axis A_2 , is accordingly found by laying off on the polar circle from the point C an angle equal to A'_1C . The intersection of the great circle through P and the point A'_2 with the plane of the optic axes is obviously the second optic axis A_2 and the angle between the two axial points, A_1 and A_2 , is the optic axial angle $2V$. The best results are obtained by this method on sections in which the optic axis A_1 is located about midway between the center and margin of the field and the point P on the achromatic brush in a similar position. As noted above, a probable error of $\pm 3^\circ$ is possible with this method even on the most favorable sections. The error is proportionately larger on poor sections.

GEOPHYSICAL LABORATORY
WASHINGTON, D.C.
March 16, 1912